Parameterization of a Two-Phase Sheet Flow Model and Application to Nearshore Morphology

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LONG TERM GOAL

The overall objective is to develop and test with laboratory and field observations a model that predicts sediment transport and morphological change in the nearshore for a range of wave conditions and sediment characteristics.

OBJECTIVES

The specific objectives of this project are to

- parameterize the wave-induced bottom stress and sediment transport rate using a two-phase sheet flow model
- couple the sediment transport model with a time-domain Boussinesq hydrodynamic model to predict beach profile evolution
- improve the two-phase sheet flow model by comparing its predictions with laboratory and field observations of sediment transport.

APPROACH

A two-phase sheet flow model [*Hsu et al.*, 2004; *Hsu and Hanes*, 2004] was utilized to study and parameterize the instantaneous sediment transport rate under field observed wave forcing in the surfzone at Duck, NC [e.g., *Elgar et al.*, 2001]. According to the two-phase model results, we conducted rational parameterizations for flow turbulence, particle intergranular stresses, and

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fluid-sediment interactions and proposed simplified approaches for wave induced sediment transport. The simplified approaches are first tested by driving the models with field measured forcing to predict observed nearshore sandbar migration events. Effective approaches for sediment transport rate are further incorporated into a Boussinesq wave model (FUNWAVE, see *Kirby* [2003] for an overview of applications) to predict surfzone hydrodynamics, sediment transport and beach profile evolution given field measured offshore wave condition and initial bathymetry. The resulting model also has been found to give qualitatively accurate predictions of onshore bar motion during accretionary transport [*Long et al*, 2004].

WORK COMPLETED

Motivated by earlier studies [e.g., *Drake and Calantoni*, 2001; *Hoefel and Elgar*, 2003] on the effects of flow acceleration on sediment transport, *Hsu and Hanes* [2004] investigated the response of sediment under waves by driving the two-phase model with several idealized wave shapes. They concluded that without the influence of breaking-wave-generated turbulence, the instantaneous sediment transport rate can be parameterized by bottom stress through a power law. However, whether the bottom stress can be easily parameterized by the quasi-steady free-stream velocity depends on wave shape. In general, the quasi-steady bottom stress is a plausible simplification for skewed wave shape. However, if the wave shapes are dominated by pitch-forward saw-tooth waves, the quasi-steady assumption between the flow forcing and bottom stress may cause significant under-prediction of onshore transport [e.g., *Drake and Calantoni*, 2001; *Nielsen and Callaghan*, 2003].

Here, the two-phase model is further driven by field observed wave forcing measured in the surfzone at Duck, NC. Specific attention is focused on the dynamics between the wave forcing and the resulting bottom stress and transport rate. According to the two-phase model results, several simplified approaches, when driven by the field measured wave forcing, were shown to be capable of modeling an observed 5-day onshore sandbar migration event. These simplified parameterizations are further incorporated into a Boussinesq wave model FUNWAVE. FUNWAVE has been coupled to a bottom boundary layer model which is run at a fine spatial resolution in the cross-shore to calculate an instantaneous bottom stress, followed by a transport rate based on the Meyer-Peter Mueller formula. Transport is then averaged for 10's of minutes and then used to update the bottom at a more appropriate morphological time step. Calculations based on a mixing length closure and linearized boundary layer equations have been completed. Given the field measured offshore wave conditions and initial bathymetry, the Boussinesq model is able to reproduce both the observed surfzone hydrodynamics and beach profile evolution during an onshore sandbar migration event. Work so far has indicated that the morphology evolution calculation can be marginally unstable, and work on the numerical aspects of this problem is being carried out.

Progress has also been made to extend further the two-phase model to simulate transport of finer sand (particle diameter $d = 0.1 \sim 0.5$mm). Preliminary model-data comparison with U-tube data measured by *Dohmen-Janssen et al.* [2002] suggests that the refined closure for turbulence-sediment interactions calibrated by the DNS results [*Squires and Eaton*, 1994] is promising. More extensive model-data comparisons for new U-tube data measured by *O'Donoghue and Wright* [2004] are currently underway.

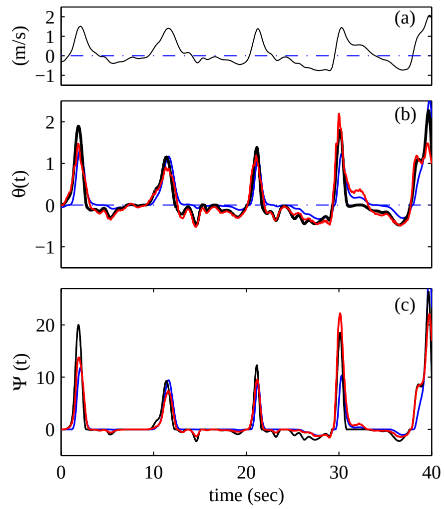

Figure 1: (a) Free stream wave-orbital velocity observed at the sandbar crest, and corresponding (b) model nondimensional bed shear stress . (the Shield's parameter), and (c) model nondimensional transport rate . versus time. The sand is coarse (d=1.1 mm, speci c gravity s=2.65). The bed shear stresses t_b, used to calculate . in (b), are from two-phase [red curve, Hsu et al., 2004], quasi-steady [blue, with best- t wave friction factor f_w = 0.02], and rst-order, single-phase with mixing-length closure [black, with best- t roughness K_s = 15d] models. At other cross-shore locations, the r^2 and best- t f_w and K_s are within about 15% of the values at the bar crest. In (c), . is shown for the two-phase model (red), and for the rst-order, single-phase (black) and the quasi-steady (blue) models coupled with Meyer-Peter Mueller power law . = 8(. - 0.05)$^{1.5}$ appropriate for coarse grains. Correlation factors are calculated based on a 300-s long simulation (of which 40 s is shown).

RESULTS

Field observed near-bed flow velocity time series (figure 1a) in the outer surfzone during Duck94 is used to drive the two-phase model and simpler models that are more computationally efficient. The performance of the simpler models is evaluated with the two-phase model results according to their prediction of bottom stress (figure 1b) and transport rate (figure 1c). The bottom stress calculated by first-order boundary layer equation with a mixing length closure is similar to the two-phase bottom stress (square correlation r^2=0.88, figure 1b). By assuming a simple quadratic relation between the bottom stress and quasi-steady flow velocity, the bottom stress calculated by the quasi-steady model is less correlated with the two-phase stress (square correlation r^2=0.7). Sediment transport rates calculated by coupling the single-phase boundary layer stress and quasi-steady stress with a Meyer-Peter Mueller power law are both similar to that obtained by the two-phase model (square correlations r^2=0.7, figure 1c). Although the flow forcing in the outer surfzone contain both skewed and saw-toothed wave shapes, the quasi-steady model under-predicts both the magnitude of bottom stress and transport rate under the passage of pitch-forward saw-tooth waves ($t = 28 \sim 35$ sec), consistent with previous studies regarding the importance of flow acceleration [e.g, *Drake and Calantoni* 2001; *Nielsen and Callaghan*, 2003; *Hoefel and Elgar*, 2003]. The roughness height $K_s = 15d$ (friction factor $f_w = 0.02$) in the boundary layer model (quasi-steady model), chosen to best fit the magnitude of the two-phase bottom stress, is significantly larger than that commonly used for clear fluid. The large roughness (friction factor) is possibly a surrogate for the additional energy dissipation due to particle collisions and fluid-particle interactions.

The single-phase boundary layer and quasi-steady models were forced with demeaned (3 hr averages) time series of velocity $\tilde{U}_0(t)$ measured about 0.5 m above the seafloor at 11 cross-shore locations extending 250 m from near the shoreline to approximately 4-m water depth (Figure 2). The calculated instantaneous bottom stress yields the sheet flow sediment transport rate through a power law [*Ribberink*, 1998], and the corresponding morphological change is updated every 3 hours. Results are presented for a spatially constant sand grain diameter ($d = 0.20$ mm), but are similar using the observed values of d, which ranged from 0.29 mm at the shoreline to 0.15 mm in 4 - m water depth [*Gallagher et al.*, 1998]. The observed onshore sandbar migration is modeled qualitatively well by both the quasi-steady model with wave friction factor $f_w = 0.009$ and by the first-order single-phase boundary layer model with mixing-length closure and roughness $K_s = 7d$ (the skill is approximately 0.4 for each model (Figure 2)). Predictions are further improved using the more accurate second-order boundary layer model [*Trowbridge and Young*, 1989] with both the mixing length (skill=0.6, $K_s = 14d$) and more complete $k - \epsilon$ (skill=0.7, $K_s = 24d$) closures (not shown).

Errors in the first-order boundary layer model owing to neglecting nonlinear terms were investigated by implementing the second-order model (with the same K_s) with and without vertical velocities and streamwise convection. The effects of vertical velocities in the second-order model improve the model skill near the sandbar crest (cross-shore position about 225 m, Figure 2) and streamwise convection terms improve model skill near the shoreline (cross-shore position from 140 to 200 m, Figure 2). These results suggest that nonlinear boundary layer processes enhance the shoreward transport of sediment near the sandbar crest, consistent with earlier studies [*Trowbridge and Young*, 1989; *Henderson et al.*, 2004].

Results of the type shown in Figure 2 indicate that the present transport formulations indicate the correct orientation of net transport, but since the transport is based on "correct" hydrodynamics measured over a "correct" bed, the question remains whether the transport rate calculations developed here would be robust in a model simulation initialized at some time and run only with incident wave conditions, with the hydrodynamics responding to the simulated bed as opposed to the "real" bed. *Long et al* [2004] have performed this calculation for the limited case of a linearized boundary layer model and the Meyer-Peter and Mueller transport formula, and for the quasi-steady model. Results are shown in Figure 3, where model results described here are indicated by heavy blue line (for the first order, single-phase boundary layer model) and dashed blue line (for the quasi-steady model), and measured bathymetry is indicated by the red line. Results are similar to the data-driven simulation results shown in Figure 2. So far, we have seen no indications that transport or morphology calculations based on the sparse cross-shore array of Duck '94 are not consistent with results from more finely resolved cross-shore models.

IMPACT/APPLICATIONS

The use of the two-phase model with field measured forcing enhances our physical understanding of sediment transport, and provide a rational approach to develop simple and effective sediment transport parameterizations. The coupled Boussinesq-sediment model, when further comprehensively tested with field data, is the first step toward developing a physical-based predictive model for large-scale nearshore sediment transport and shoreline change.

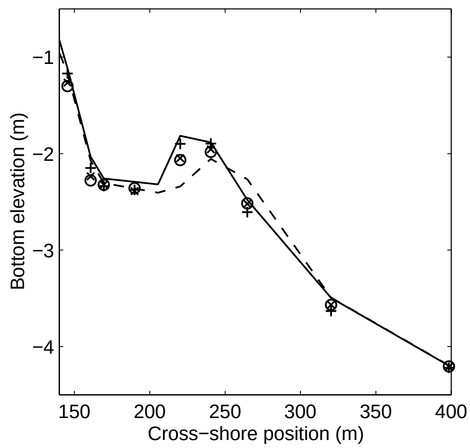

Figure 2: Bottom elevation versus cross-shore position observed September 22 (dashed curve) and September 27 (solid curve) 1994. Symbols are model predictions of the September 27 pro le initialized with the September 22 pro le and driven with near-bottom wave-orbital velocities observed between 1900 September 22 and 2200 September 27. Crosses are the quasi-steady model with a wave friction factor f_w = 0.009, circles are the rst-order single-phase ow model with a mixing-length closure (K_s = 7d), and plusses are the second-order model with mixing-length closure (K_s = 14d). The values of f_w and K_s are selected to maximize the model agreement with the observations. The quasi-steady and rst-order models have similar skills (0.35 and 0.40, respectively), whereas the second-order model (plusses) has higher skill (0.60). Average (3-hr) bottom elevations were obtained with altimeters colocated with pressure gages and current meters at the cross-shore positions with symbols [Gallagher et al., 1998].

RELATED PROJECTS

Field data collected during Duck94 and SandyDuck is extensively used to guide the development and calibration of the models.

The NOPP project "Development and Verification of a Comprehensive Community Model for Physical Processes in the Nearshore Ocean" has developed the model system NearCoM, which uses FUNWAVE as one of its circulation model components. The results from this study will be directly added to that publically available system as part of this project.

PIs Hsu and Kirby are involved in a collaborative research project CROSSTEX for surfzone hydrodynamics, sediment transport and morphological evolution. The prototype laboratory experiment will be conducted in Summer 2005 at O.H. Hinsdale Wave Research laboratory of the Oregon State University. The major modeling components for CROSSTEX were proposed by Hsu (Co-PI: John Trowbridge) to ONR Coastal Geoscience Program. Kirby is taking part in long term morphology change tests, which will be used to test predictions made with the models being developed here. The sediment transport parameterization and model development conducted in this research will be influential to the CROSSTEX project.

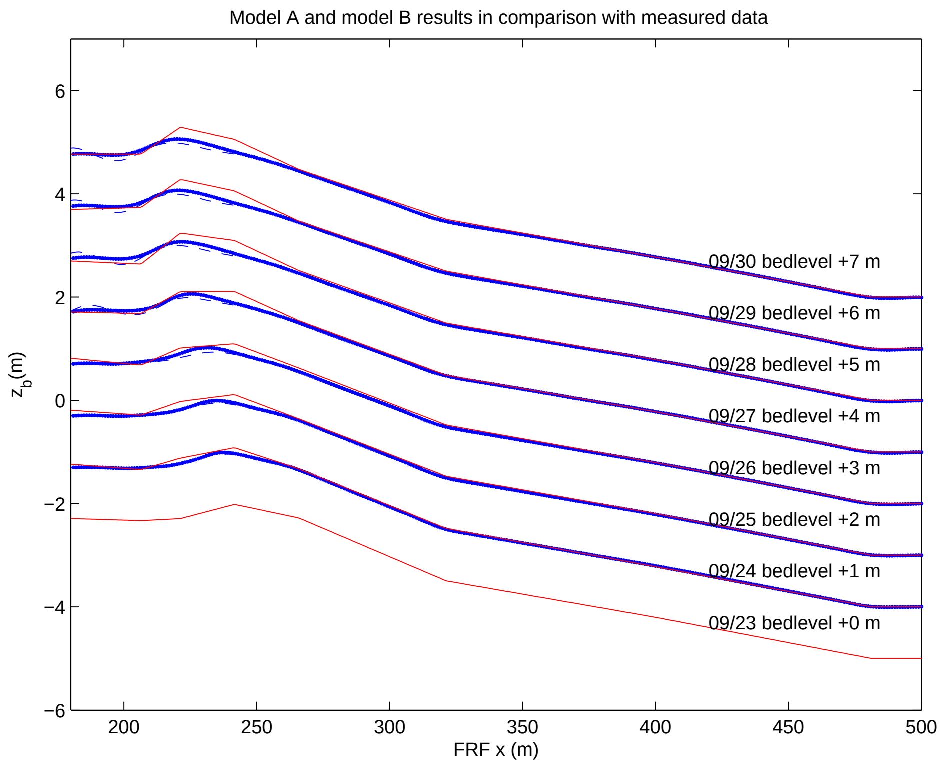

Figure 3: Duck '94 onshore bar migration. Pro le change predicted by FUNWAVE coupled to a time-resolved bottom boundary layer model. Model A (dashed blue line) indicates results calculated with the Bagnold formula with no acceleration correction (the quasi-steady model), using FUNWAVE-predicted bottom velocities. Model B (solid blue line) indicates results for the rst order boundary layer model and MPM transport formula. Red line is measured eld bathymetry (from Long et al [2004]).

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